Gamma Ray Bursts via emission of axion-like particles

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The Pseudo-Goldstone Boson (PGB) emission could provide a very efficient mechanism for explaining the cosmic Gamma Ray Bursts (GRBs). The PGBs could be produced during the merging of two compact objects like two neutron stars or neutron star - black hole, and then decay into electron-positron pairs and photons at distances of hundreds or thousands km, where the baryon density is low. In this way, a huge energy (up to more than 10^{54} erg) can be deposited into the outer space in the form of ultrarelativistic e^+e^- plasma, the so called fireball, which originates the observed gamma-ray bursts. The needed ranges for the PGB parameters are: mass of order MeV, coupling to nucleons $g_{aN} \sim$ few $\times\, 10^{-6}$ and to electrons $g_{ae} \sim$ few $\times\, 10^{-9}$. Interestingly enough, the range for coupling constants correspond to that of the invisible axion with the Peccei-Quinn symmetry breaking scale $f \sim$ few $\times\, 10^5$ GeV, but the mass of the PGB is many orders of magnitude larger than what such a scale would demand to an axion. Neither present experimental data nor astrophysical and cosmological arguments can exclude such an ultramassive axion, however the relevant parameters' window is within the reach of future experiments. Another exciting point is that our mechanism could explain the association of some GRBs with supernovae type Ib/c, as far as their progenitor stars have a radius $\sim 10^4$ km. And finally, it also could help the supernova type II explosion: PGB emitted from the core of the collapsing star and decaying in the outer shells would deposit a kinetic energy of the order of 10^{51} erg. In this way, emission of such an axion-like particle could provide an unique theoretical base for understanding the gamma ray bursts and supernova explosions.

DFAQ-TH/99-05
INFN-FE/12-99

1. Introduction

The phenomenon of the so-called Gamma-Ray Bursts (GRBs) puzzles the theorists from many points of view (for a review see [1]). The most striking feature of GRBs is that an enormous energy is released in few seconds in terms of gamma-rays having typical energies of few hundred keV. The energy emitted in GRBs is up to 10^{53-54} erg, making it difficult to devise a mechanism able to transform efficiently enough the gravitational energy into such a powerful photon emission. In addition, the bursts show a variety of complex time-structures of the light curves. The time-structure of the prompt emission and the recent discovery of the afterglow fit the expectations of the so-called fireball model [2], in which the electromagnetic radiation is originated from the electron-positron plasma that expands at ultrarelativistic velocities undergoing internal and external shocks. The Lorentz factor of the plasma has to be very large, $\Gamma \sim 100$, in order to solve the so-called compactness problem [3]. So large values of Γ are difficult to achieve because they require a very efficient mechanism to accelerate the plasma. In addition, in order to avoid the contamination of the e^+e^- plasma by more massive matter, the plasma has to be produced in a region of low baryonic density.

Several mechanisms have been proposed to power the e^+e^- plasma. In particular, it could be obtained via annihilation $\nu\bar{\nu} \to e^+e^-$ of the neutrinos emitted by a heavy compact collapsing object – collapsar [4–6]. Alternatively, neutrinos can be produced at the merger of two compact objects, e.g. of two neutron stars [7] or a neutron star and a black hole [8]. The latter possibilities were recently analyzed in details in refs. [9–11]. [1]

The main challenge to the existing models is that the energy released in photons is astonishingly large. For example, the Gamma-Ray Burst GRB 990123 shows an energy release $\mathcal{E} \simeq 3.4 \times 10^{54}$ erg $= 1.9 M_\odot$, if isotropic emission is assumed. Taking into account a possible beaming, this energy can be reduced down to $\mathcal{E} \simeq 6 \times 10^{52}$ erg [13]. There are also few other events (e.g. GRB 971214 and GRB 980703) with typical energies $\mathcal{E} \sim 10^{53}$ erg, which show no evidence for collimation [14]. The models invoking the $\nu\bar{\nu} \to e^+e^-$ reaction as a source for the GRB have strong difficulties in reaching so large photon luminosities. Although during the collapse of compact objects a relevant amount of energy is normally emitted in terms of neutrinos, the low efficiency of the $\nu\bar{\nu} \to e^+e^-$ reaction strongly reduces the energy deposited in the fireball.

In the present paper we propose that light pseudoscalar particles – Pseudo-Goldstone Bosons (PGBs) – can be extremely efficient messengers for transferring the gravitational energy released in the merger of compact stars, into ultrarelativistic e^+e^- plasma. We show that for certain parameter ranges the PGBs can be effectively produced inside the dense core of the collapsing system and then decay into $\gamma\gamma$ or e^+e^- outside the system, in baryon free zones, thus giving rise to the ultrarelativistic e^+e^- plasma.

The advantage of assuming that the fireball is produced via the PGB decay instead of $\nu\bar{\nu} \to e^+e^-$ annihilation is obvious. The latter process has a low efficiency – neutrinos deposit to plasma only few percent of the emitted energy and take the rest away. In addition, the process $\nu\bar{\nu} \to e^+e^-$ can be effective only at small distances, less than 100 km, which are still contaminated by baryon load, and it fails to provide a sufficiently large

[1] Recently some exotic mechanisms have been suggested related to the gravitational collapse of mirror stars [12].

Lorentz factor to the plasma, at most $\Gamma \sim 5$ [9,10]. Instead, the PGB mechanism is 100 percent efficient: decay can take place at distances about 1000 km and, in addition, all energy emitted in terms of PGBs is deposited to the e^+e^- plasma with the Lorentz factor $\Gamma \sim E/m_e$, where E is a typical energy of emitted PGBs (tens of MeV) and m_e is the electron mass. This analysis is supported by the very recent result of ref. [15], which shows that if the energy would be transfered to the plasma at distances of at least few hundreds km, a successful burst could be obtained with a Lorentz factor ~ 40 or so.

The most familiar example of a PGB, the axion [16,17], has already been considered in connection with GRBs [18]. However, this was an invisible axion with the mass $m_a \sim 10^{-5}$ eV. Such an axion has a lifetime much larger than the age of the universe and thus its decay is impossible. Instead, it was assumed that the axions could convert into photons in strong magnetic fields near the collapsing system. It is questionable, however, how large the magnetic field has to be in order to achieve a large efficiency for the conversion.

In our analysis we phenomenologically consider a more general possibility, assuming that the PGB mass m_a and its couplings to nucleons, electrons and photons are not constrained by the Peccei-Quinn relations. The paper is organized as follows. In section 2 we shortly review the results of refs. [9–11] which describe the general scenario for mergers. In section 3 we consider the PGB emission as a source for the GRB and discuss the ranges for its mass and couplings which are compatible with the existing astrophysical constraints. In section 4 possible models for such axion-like particles are discussed. In section 5 we analyze possible signatures of the proposed mechanism. In particular, we show that the PGBs emission could generate a GRB associated with the supernovae type Ib,c, and also help the supernova type II explosion. Finally, in section 6 we summarize our findings.

2. NS-NS and NS-BH mergers

The scenarios depicted in refs. [9–11] for the NS-NS and NS-BH mergers are actually very similar. In both cases an axially symmetric structure develops. In the center the system collapses into a black hole of a few solar masses, while a fraction of matter ($M \sim 0.1 M_\odot$ for NS-NS and $M \sim 0.5 M_\odot$ for NS-BH) obtains enough angular momentum to resist immediate collapse into the black hole and remains in an accretion torus around the black-hole. Then this mass accretes from the torus into the BH going through a disk-like structure having a thickness which decreases approaching the BH. The central part of the disk is the most relevant for the radiation of energy, being the reservoir of largest density and temperature. The accretion rate from the torus dM/dt is of the order of 1 $M_\odot$/s for NS-NS and 5 $M_\odot$/s for NS-BH, so the duration of this phase is essentially similar in both cases, $t \sim 0.1$ s.

According to refs. [9–11], the energy is radiated from the disk via the neutrino emission. The deposition of energy in a region with low baryonic mass proceeds through $\nu\bar{\nu}$ annihilation into e^+e^-. The observed GRB is produced by the e^+e^- plasma which expands at ultra-relativistic velocity. The energy deposited into the e^+e^- plasma ranges from $E_{\nu\bar{\nu}} \sim 10^{48-49}$ erg in the case of NS-NS merger up to $E_{\nu\bar{\nu}} \sim 10^{51.6}$ erg for the NS-NH merger. The Lorentz factor are always rather small, $\Gamma \sim 5$.

An important point in the simulations of refs. [9,10] concerns the density and temper-

ature profiles of the system. In ref. [9], where the neutrino trapping has been taken into account, the maximum density is $\sim 10^{11}$ g/cm^3, with small regions reaching 10^{12} g/cm^3. On the contrary, in ref. [10] where neutrinos are assumed to skip freely, densities are generally smaller by about an order of magnitude. When neutrino trapping is taken into account, larger densities, similar to the ones in ref. [9], are obtained. In ref. [10] it is indeed shown that the density of the disk depends on the amount of energy lost by matter in this region. It is clear that only a totally self-consistent calculation can indicate if neutrinos are trapped, reducing the luminosity of neutrino emission and therefore allowing for a larger density in the center of the disk. The connection between cooling and density is due to the contribution to the pressure coming from radiation and relativistic electrons and positrons. If the cooling is switched-off, only gas pressure is present and the system stabilizes at larger densities.

It will be important in our discussion to keep in mind that a more efficient way of extracting energy from the system, e.g. via PGBs emission, will in turn modify the density in the center of the disk. Since in our work we do not pretend to solve the dynamics of the system, but we only indicate a new possibility for powering a strong GRB, we will consider for the central density of the disk values ranging from $\sim 10^{11}$ g/cm^3 down to 10^9 g/cm^3.

The estimated temperature profiles of the disk are rather similar in refs. [9] and [10], reaching about 10 MeV in the central part and remaining above 1 MeV up to distances of the order of 100 km from the center of the system.

3. GRB via PGB emission

Let us consider the following Lagrangian describing the PGB couplings to the fermions ψ_i $(i = e, p, n, ...)$ and electromagnetic field-strength tensor $F_{\mu\nu}$:

$$\mathcal{L} = -\frac{1}{2} m_a^2 a^2 - i g_{ai} a \bar{\psi}_i \gamma_5 \psi_i - \frac{g_{a\gamma}}{4 m_N} a F_{\mu\nu} \tilde{F}^{\mu\nu} + ... \quad (1)$$

where in the last term the nucleon mass m_N is taken as a regulator scale. In cases of the familiar models of the PGB like the axion, its mass and couplings are all determined, but for some coefficients, by only one free parameter f, the scale of the global $U(1)_{PQ}$ symmetry. Instead, here we take a more phenomenological approach, considering m_a, $g_{a\gamma}$, g_{aN} and g_{ae} as independent quantities.

Let us start by discussing which constraints should be imposed immediately on the PGB mass and its couplings in order to obtain a strong GRB without violating the already existing experimental and astrophysical limits. In particular, we consider the mass and the coupling to the nucleon within the range

$$0.3 \text{ MeV} < m_a < \text{few MeV} \quad (2)$$

$$10^{-6} < g_{aN} < 10^{-4} \quad (3)$$

The upper mass limit comes from the following. In order to have efficient PGB production in the dense systems under consideration, its mass should not over-exceed the characteristic temperature of the latter, typically of few MeV. The lower mass limit in (2) enables

to avoid the astrophysical constraints from the stellar evolution. The PGB production rate in the stellar cores with typical temperatures T up to 10 keV, is proportional to $g_{aN}^2 \exp(-m_a/T)$. Thus, in order to avoid too fast stellar cooling, the exponential factor needs to be small if the constant g_{aN} falls in the range indicated in (3). The lower limit on g_{aN} comes from supernovae. It implies that the PGBs are trapped in the collapsing core and thus the SN 1987A neutrino signal is not affected [19].[2] Finally, the upper limit in (3) stands for a conservative interpretation of the set of constraints coming from the search of the decay $K^+ \to \pi^+ a$, from the beam dump and other terrestrial experiments [20]. The experimental limits on the couplings g_{ae} and $g_{a\gamma}$ will be discussed later.

Let us discuss now in more details the range of the PGB parameters needed for successfully producing the GRBs.

Mean lifetime

The PGB can decay into photons and, if $m_a > 2m_e$, also into e^+e^-. The corresponding decay width is $\Gamma_{\rm tot} = \Gamma(a \to \gamma\gamma) + \Gamma(a \to e^+e^-)$, where

$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma}^2}{64\pi m_N^2} m_a^3, \tag{4}$$

$$\Gamma(a \to e^+e^-) = \frac{g_{ae}^2}{8\pi} m_a \left(1 - \frac{4m_e^2}{m_a^2}\right)^{1/2}. \tag{5}$$

As we anticipated in the introduction, we discuss the emission of PGBs by the central part of the toroidal system with typical size ~ 100 km, obtained during the merger of two compact objects. We assume that these PGBs take away a large fraction of the energy of the system and we want them to decay into photons or e^+e^- preferentially outside the disk, in the region of low baryon density, thus giving rise to the hot relativistic plasma. Therefore a reasonable choice for the decay length of the PGBs, $D_a = c\tau\gamma$, is in the range

$$100 \text{ km} < D_a < 10000 \text{ km}. \tag{6}$$

Here $\tau = \Gamma_{\rm tot}^{-1}$ is the lifetime of the PGB at rest and $\gamma = E/m_a$ is its Lorentz factor. The average energy of the emitted PGBs can be taken as $E \simeq 3T$, where T is a temperature of the system. Since T is of the order of several MeV, the Lorentz factor γ ranges from 2-3 up to 20 or more, depending on the mass of the PGB. The values of $g_{a\gamma}$ and g_{ae} corresponding to a given decay length D_a, as functions of m_a, are shown in Fig. 1.

The upper limit in (6) is not rigidly determined and is inferred from the following. In the literature it is argued that there is a correlation between some GRBs and supernovae type Ib/c [21,22]. On the other hand, the observed frequency of supernova explosions is orders of magnitude larger than the observed frequency of GRBs. Therefore not every SN explosion is accompanied by a detected GRBs. If a supernova type Ib/c emits a GRB, the latter must be a rather weak one, so that it is detected only in few cases. Therefore, D_a should be less than the typical radius of the type Ib/c supernova progenitors ($R \sim 10^4$ km), so that the strength of the associated GRB is suppressed by a factor $\exp(-R/D_a)$.

[2]The region $g_{aN} \leq 10^{-11}$ is also acceptable for the constraints coming from neutrino emission in supernovae [19], but is not of interest for our analysis.

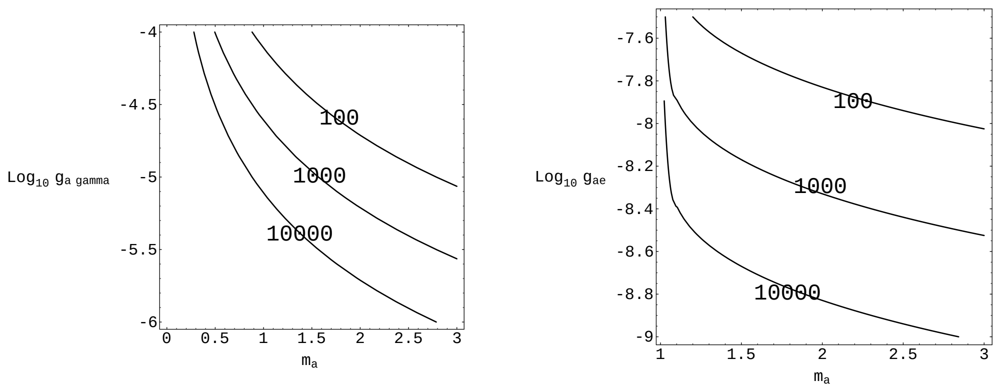

Figure 1. $g_{a\gamma}$ and g_{ae} as functions of m_a[MeV], for the given decay length ($D_a = 10^2$, 10^3 and 10^4 km). The PGB energy taken is $E = 15$ MeV.

Obviously, this suppression is enormous in the case of SN type II which progenitor has a typical radius larger than 10^7 km. In particular this makes clear the absence of a detectable GRB associated with SN 1987A.

Mean free path

The mean free path of a PGB having energy E depends on the density ρ and on the temperature T of matter, on the neutron and proton mass fractions X_n and X_p and, of course, on the PGB coupling to nucleons g_{aN}. (Here and in the following, we take for simplicity the PGB couplings to proton and neutron to be equal, $g_{ap} = g_{an} = g_{aN}$). In ref. [23] the mean free path is approximated by the following expression:

$$\lambda_a = g_{aN}^{-2}\ F(X_n, X_p, E/T)\ l_a(\rho, T), \tag{7}$$

where the coefficient $F = (1 + 8X_nX_p)^{-1}\,(E/T)\,(1 + E/T)^{-1/2}$ is of order 1 for typical energies $E \sim 3T$ and

$$l_a = (2.8 \times 10^{-7}\ \text{cm}) \times \rho_{12}^{-2}\, T[\text{MeV}]^{1/2}, \tag{8}$$

with ρ_{12} being the density in units of 10^{12} g/cm^3.

For a given density and temperature one can estimate the critical value of g_{aN} for which the PGBs become trapped. We denote this value as $g_{aN}^{tr}(\rho, T)$. Clearly, only an exact knowledge of the density and temperature profiles of the system can allow a precise determination of this quantity. However, we are only interested in a qualitative analysis and in our estimate we simply assume that the PGB is trapped when λ_a is smaller than the typical radius of the system $R \sim 50$ km. In other words, we define the critical value

g_{aN}^{tr} as a function of a given density and temperature from the following equation[3]

$$(g_{aN}^{tr})^{-2}\, l_a(\rho,T) = R. \tag{9}$$

Hence, using eq. (8) we obtain:

$$g_{aN}^{tr}(\rho,T) = 2.4\times 10^{-7}\rho_{12}^{-1}T[\mathrm{MeV}]^{1/4}, \tag{10}$$

Assuming for instance $T = 5$MeV and $\rho \sim 10^{11}$ g/cm^3, the PGBs are un-trapped for $g_{aN} \le g_{aN}^{tr} = 3.6\times 10^{-6}$. If the density is smaller, g_{aN}^{tr} increases. E.g., for $\rho \sim 10^{10}$ g/cm^3, $g_{aN}^{tr} = 3.6\times 10^{-5}$, while for $\rho \sim 10^9$ g/cm^3, $g_{aN}^{tr} = 3.6\times 10^{-4}$.

Emission rate

In the conditions of density and temperature typical for the central region of the disk, baryonic matter is non-degenerate, and the PGB production is dominated by bremsstrahlung from nucleons. The analogous process from electrons is less efficient, also because the latter are partially degenerate at the densities and temperatures we are considering here. We use for the PGB production rate the expression [19]:

$$Q_{ND} = g_{aN}^2 R_{ND}(\rho,T) = g_{aN}^2\frac{272\alpha_\pi^2}{105\pi^{3/2}}\frac{T^{7/2}\rho^2}{m_N^{9/2}} = g_{aN}^2\rho_{12}^2 T[\mathrm{MeV}]^{7/2}\times 2.3\cdot 10^{45}\ \mathrm{erg/cm^3 s} \tag{11}$$

where, for simplicity, we consider symmetric nuclear matter, i.e. $K_{Fn} = K_{Fp} \equiv K_F$, and $\alpha_\pi \sim 15$ is the pion-nucleon coupling constant [19]. In Fig. 2 we show $\mathrm{Log}_{10}(R_{ND}$[erg cm^{-3} s^{-1}]) as a function of the temperature and of the density.

Let us now estimate the maximal possible luminosity of the PGB emission as a function of g_{aN}. Clearly, if the PGBs are emitted from a volume with given density and temperature in un-trapping regime, then their luminosity increases with g_{aN} and reaches the maximum at $g_{aN} = g_{aN}^{tr}(\rho,T)$. For the values of g_{aN} larger than g_{aN}^{tr}, the PGBs become trapped and their luminosity starts to decrease, since only the PGB emission from the surface becomes possible. To compute the total luminosity we need also to estimate a corresponding volume associated with the un-trapped regime.

The maximal luminosity for a volume $V(\rho,T)$ with a given density and temperature reads therefore:

$$L_a^{max} = [g_{aN}^{tr}(\rho,T)]^2\times R_{ND}(\rho,T)\times V(\rho,T) \tag{12}$$

We use the results of ref. [9] to estimate the magnitude of the maximal luminosity. Let us consider, for example, the central zone with $\rho \simeq 10^{11}$ g cm^{-3} and $T \simeq 3$ MeV. The corresponding volume is roughly $V \sim 10^6$ km^3. Then, according to eq. (10) we obtain $g_{aN}^{tr} = 3.3\times 10^{-6}$, and thus we get $L_a^{max} \sim 10^{56}$ erg/s, clearly a very large value which would be sufficient to power the most energetic bursts.[4] It can be interesting to notice

[3] Taking into account that regions with high densities are smaller than R, the values we find for g_{aN}^{tr} are clearly underestimated with respect to the actual values by a factor $\sqrt{R/R(\rho,T)} \sim$ few, where $R(\rho,T)$ is the actual size of the region having a given density and temperature. However, this approximation is sufficient to our purposes.

[4] Certainly, such an enormous luminosity is unphysical. The actual luminosity should not exceed the rate of the mass transfer which, for NS-NS merger is $dM/dt \simeq 1\ M_\odot$ s^{-1} $= 1.5\cdot 10^{54}$ erg s^{-1}. As we noted above, in case of the NS-BH merger the later rate is about 5 times bigger.

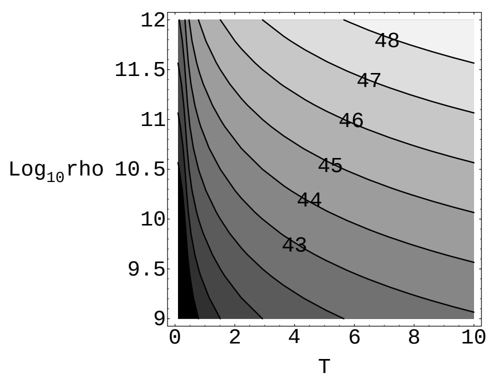

Figure 2. Isocontours for $\mathrm{Log}_{10}(R_{ND}[\mathrm{erg/cm^3 s}])$ as a function of the temperature T[MeV] and of the density $\rho[\mathrm{g/cm^3}]$.

that R_{ND} is proportional to ρ^2, while g_{aN}^{tr} is roughly proportional to ρ^{-1} as is indicated by eqs. (9) and (8). Hence, the maximal luminosity very weakly depends on the central density.

Of course, the actual luminosity can be smaller. E.g., for $g_{aN} < g_{aN}^{tr}$ the emission rate is simply proportional to g_{aN}^2. If, on the other hand, $g_{aN} > g_{aN}^{tr}(\rho, T)$, then the emission rate is suppressed due to the PGB trapping. In this case the volume in which the PGBs are trapped becomes ineffective, since now it contributes only through the surface emission, and so the dominant contribution comes from outer zones with smaller densities in which PGBs are still un-trapped. It is difficult to estimate the emission rate in the trapping regime. Taking, for example, $g_{aN} = 3 \times 10^{-5}$, i.e. one order of magnitude larger then previous value, one can roughly estimate the total luminosity as $L_a \sim 10^{55}$ erg/s, one order of magnitude less then above.

Therefore, a luminosity larger than $\frac{1}{10} L_a^{max} \sim 5 \times 10^{54}$erg/s can be obtained for g_{aN} in the range:

$$10^{-6} < g_{aN} < 3 \times 10^{-5}. \tag{13}$$

It is important to notice that, since the PGB luminosity is so large, a precise determination of the latter is inessential. Actually, for this range of g_{aN} the PGB emission drains all the energy available from the system.

For sake of simplicity in our analysis we have mainly considered the density and temperature profiles which are characteristic for the NS-NS merger. Let us shortly comment also the case of NS-BH merger. The latter gives somewhat larger densities and temperatures than the NS-NS merger. As observed above, a change in the density is not affecting the maximal luminosity L_a^{max}. A slightly larger temperature, on the other hand, corresponds to a larger production rate Q_{ND} and therefore to a larger luminosity.

4. The PGB models

Let us discuss now which particle physics candidate could be the PGB with the above properties. As we told already, the most familiar example is the axion, the PGB associated with the spontaneous breaking of the Peccei-Quinn symmetry $U(1)_{PQ}$ needed for the solution of the strong CP-problem. The standard axion [16] is excluded by laboratory experiments long ago. However, several types of invisible axions have been considered in the literature: the DFSZ axion [24], the KSVZ or hadronic axion [25], archion [26], etc. In these models the PQ symmetry is spontaneously broken due to the large VEV of some scalar S, singlet of the standard model: $\langle S \rangle = f/\sqrt{2}$. The axion interactions to matter fields have the form (1) where the coupling constants to the fermions and photon are related to the scale f as follows:

$$g_{ai} = c_i \frac{m_i}{f} \quad (i = e, p, n...), \qquad g_{a\gamma} = c_\gamma \frac{\alpha}{2\pi} \frac{m_N}{f}, \tag{14}$$

with c_i and c_γ being the model dependent coefficients (generically, axion models employ a number of heavy fermion states that contribute to the colour N and electromagnetic E anomalies of the $U(1)_{PQ}$ current). For any type of axion, its couplings to nucleons do not vary strongly from model to model and, typically, $c_{p,n}$ are in the range 0.3–1.5. As for g_{ae} and $g_{a\gamma}$, their model dependence is stronger. For example, for the DFSZ axion model containing only the standard fermion families ($N = N_f$ is the number of families, and $E/N = 8/3$) we have

$$c_e^{DFSZ} = \sin^2 \beta, \qquad c_\gamma^{DFSZ} = \frac{2N_f z}{1+z}, \tag{15}$$

where $\tan\beta = v_u/v_d$ is the VEV ratio of the up and down Higgs doublets H_u and H_d. Thus, for $N_f = 3$ and a natural range $v_u/v_d \geq 1$, c_e varies from 1/2 to 1, while c_γ depends on the value of up/down quark mass ratio $z = m_u/m_d = 0.3 - 0.7$. Therefore, $g_{ae}/g_{a\gamma} = 0.47 c_e/c_\gamma$ can vary between 0.10 and 0.35. On the other hand, for the DFSZ-like axion we have $g_{aN} = (c_N m_N / c_e m_e) g_{ae} \sim (10^3 - 10^4) g_{ae}$.

For the hadronic axion or the archion the coupling to electrons is strongly suppressed. For example, for the hadronic axion $g_{ea} = 0$ at tree level and it emerges from radiative corrections. Namely, we have [17]

$$c_e = \frac{3\alpha^2}{4\pi} \left(E \ln \frac{f}{\Lambda} - c_\gamma \ln \frac{\Lambda}{m_e} \right), \qquad c_\gamma = E - \frac{2(4+z)}{3(1+z)} N, \tag{16}$$

where $\Lambda \simeq 1$ GeV is a QCD scale. In the GUT context one typically has $E/N = 8/3$, however this value is not mandatory for a general case. Essentially the same order estimates hold for the archion couplings, which in addition can have also a small tree level coupling to electron, with $c_e = O(m_e/m_\tau) \sim 10^{-3}$ [26].

On the other hand, the axion mass is also related to the PQ symmetry breaking scale as $m_a \simeq N m_\pi f_\pi / f$ and thus for $f \sim 10^5$ GeV it is too light to be applicable for our mechanism. However, we do not constrain the magnitude of m_a with this relation and leave it as free parameter, in the range indicated in (2). In the context of a theory having the $U(1)_{PQ}$ symmetry, this would mean that the axion mass is not determined by

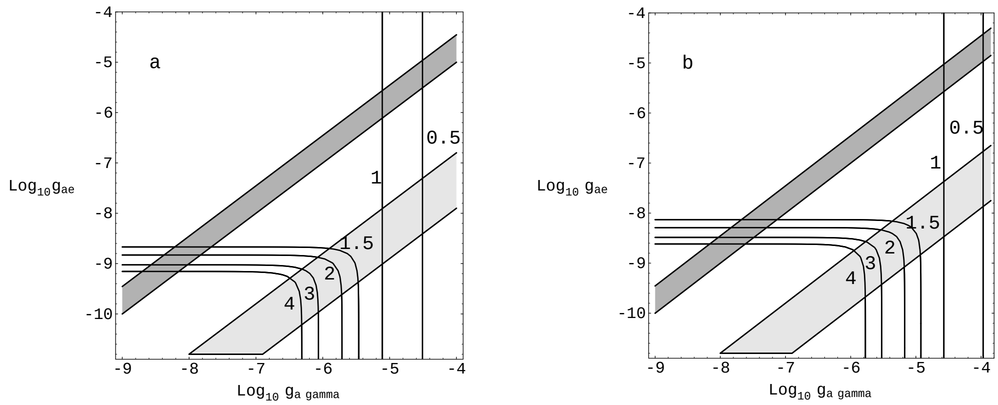

Figure 3. Possible values of g_{ae} and $g_{a\gamma}$ for a given decay length and axion energy: $D_a = 10^4$ km, E=15 MeV (a) and $D_a = 500$ km, E=9 MeV (b), for different values of the mass m_a=0.5,1, ..., 4 MeV. Shaded areas indicate typical correlations between g_{ae} and $g_{a\gamma}$ for the DFSZ axion (dark) and hadronic axion or archion (light) models.

the colour anomaly but rather by some other dynamics. For example, one can imagine that its mass emerges from the $U(1)_{PQ}$ current anomaly related to some hidden gauge sector with the confinement scale larger than Λ (in this case this axion would solve the strong CP problem in this sector). Alternatively, the Lagrangian could contain the higher order terms cutoff by the Planck scale which explicitly break the PQ symmetry and thus produce the PGB mass [27]. In either case, such PGB would not be anymore relevant for the strong CP problem. One can rather consider it as a "would be" axion which could work for strong CP but is prevented to do so by the explicit $U(1)_{PQ}$ breaking terms which in general have no reason to respect the strong θ phase orientation.

For example, taking the Planck scale induced terms in the Lagrangian as $\lambda(S^+S)^2S/M_P$, where λ is a coupling constant, one can estimate the PGB mass as [27]

$$m_a = \sqrt{\lambda}\, \left(\frac{f}{10^5\ \mathrm{GeV}}\right)^{3/2} \times 6\ \mathrm{MeV} \tag{17}$$

Although the coincidence most probably is simply accidental, we remark that for the DFSZ-like "failed" model with f = few $\times\, 10^5$ GeV (and hence $g_{ae} \sim$ few $\times\, 10^{-9}$, $g_{aN} \sim$ few $\times\, 10^{-6}$), the PGB mass in eq. (17) naturally falls in the range of few MeVs.

We come now back to the analysis of our constraints on the PGB couplings, interpreting these constraints in the light of the above discussed models. In Fig. 3 we show the isocurves corresponding to a fixed decay length D_a of the PGB with a given energy E, for different values of m_a. We also indicate typical correlations between the couplings g_{ae}

and $g_{a\gamma}$ as they emerge for various axion models.

We see that there can be two type of solutions. For the DFSZ axion it is definitely the case of decay into e^+e^- which can work. It corresponds to values of the constant $g_{ae} \sim$ few10^{-9}, i.e. $f \sim$ few $\times\ 10^5$ GeV and axion mass of few MeV. Interestingly, the parameters range excluded by the present reactor experiments [28] is approaching the parameters spot we are indicating, but the parameters value we are suggesting is not yet excluded. It must also be remarked that for such values of f the axion-nucleon coupling constant lies within the range of interest for the GRB, $g_{aN} \sim$ few $\times\ 10^{-6}$.

Another solution for the DFSZ, via axion decay into photons (vertical lines in Fig. 3 for $m_a < 1$ MeV) leads to $g_{ae} > 10^{-7}$ which is ruled out by experiment [28].

As for the case of the hadronic axion or archion, which have a coupling to electrons suppressed by 3-4 orders of magnitude if compared to the DFSZ axion, the decay rate into photons is comparable to that into e^+e^- when the latter is allowed ($m_a > 2m_e$). However, it requires a too large $g_{a\gamma}$, above 10^{-7}. The experimental limit of ref. [29], $f > 1$ TeV, excludes this possibility. Perhaps, this solution is still allowed with a larger axion mass, $m_a > 5$ MeV, but this question needs an additional investigation.

5. GRB and Supernovae

In the previous sections we have considered GRBs emerging by axion emission during a NS-NS or NS-BH merger. However, the proposed mechanism can have strong implications also for the GRBs associated with supernova explosion, as well as for the supernova explosion itself.

In the typical situation we considered, axions produced in a compact disk fly away taking the big portion of the available energy. In case of merger the typical size of the system is of the order of 100 km – there is essentially no baryonic matter outside this radius, so the axion flux, after decay into photons or e^+e^- at a distance larger then 100 km, converts into a fireball – a bubble (or jet) of hot relativistic plasma expanding with a large Lorentz factor.[5]

However, the axions can be produced also in the core of collapsing stars. In particular, for $g_{aN} \sim 10^{-6}$ the axions are essentially in the trapping regime in the supernovae exploding via core collapse. Axions are emitted from the axiosphere, having a temperature decreasing with time from $T \simeq 4$ MeV at $t = 100$ ms to $T \simeq 3$ MeV at $t = 1$ s. The corresponding luminosities are $L_a \sim 3 \cdot 10^{51}$ erg/s at $t \sim 100$ ms and $L_a \sim 0.5 \cdot 10^{51}$ erg/s at $t \sim 1$ s [23]. Therefore, in total an energy $\sim 10^{51}$ erg can be emitted during the collapse period and subsequent cooling of the proto-neutron star, in terms of axions having an average energy $E \sim 10$ MeV. Since E is of the same order as the one in case of mergers, the value $D_a = c\tau\gamma$ is again of the order of few hundred or few thousand km. Then in our scenario the impact of the axions simply depends on the geometrical size of the collapsing star.

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[5] A possible speculation concerns the observed spectrum of GRBs. The latter display a characteristic paucity for energies below few tens of keV. Moreover it typically has a maximum (the hardness H [30]) for energies of the order of few hundreds keV. Although it is not clear if there is any relation between the "internal engine" and the observed spectrum, we cannot avoid to remark a similarity between the typical value of the hardness and the mass of the PGB we have discussed in this paper.

In particular, supernovae type Ib,c are the result of core collapse of relatively small stars, where the hydrogen and perhaps also the helium shells are missing. A typical radius for SN Ic is $R \sim 10^4$ km. Therefore, the axion decay length $D_a = c\,\tau\gamma$ is comparable to R. This in turn implies that $\exp(-R/D_a)$ is not very small, it can be of order 0.1 to 1, and thus a reasonable amount of axions decay outside the mantle. Clearly, this also implies that the bulk of axions decaying outside the star produces a fireball (with a Lorentz factor $\Gamma \ \sim 3\ T/2\ m_e$). We can conclude that, associated with a supernova type Ib,c a GRB could take place, having a typical energy $\sim 10^{51}$ erg.

In case of SN type II, which are associated with large stars, e.g. red giants, having an extended hydrogen shell ($R \sim (1-20) \times 10^7$ km), the axion decay takes place completely inside the mantle and thus cannot be observed as GRB. For example, for SN 1987A, related to the blue giant Sanduleak having $R = 3 \cdot 10^7$ km, the fraction of axions decaying outside the envelope, $\exp(-R/D_a)$, is essentially zero. Nevertheless, it can be of interest to think that the energy of order 10^{51} erg released after axion decay at distances of few hundred or thousand km can help to solve the painful problem of mantle ejection and therefore of supernova explosion (in the prompt mechanism, shock stalls at a distance of few hundred km).[6]

6. Summary and conclusions

We have shown that it exists a range of values for the PGB parameters such that a strong PGB emission takes place during the NS-NS or NS-BH merger. Choosing appropriately the parameters' value, the total luminosity for the PGB emission can be as large as few $\times$ 10^{55} erg/s. Moreover, at variance with the mechanism based on $\nu\bar{\nu} \to e^+e^-$ annihilation which has a small (about one percent) efficiency, the PGB emission mechanism suffers no energy deficit: all emitted PGBs, due to their decay into e^+e^- or photons, convert into the ultrarelativistic plasma, the fireball, which is at the origin of the burst. This plasma can be produced at distances as large as 100 km $< D_a <$ 10000 km (which are difficult to achieve in the case of plasma produced via $\nu\bar{\nu}$ annihilation), is not contaminated by baryonic matter and thus a large Lorentz factor can be obtained. Our conclusion is supported by the numerical simulations given in the recent ref. [15].

An interesting possibility opened by our mechanism is the association of "weak" GRBs with the supernovae type Ib,c. In addition, the PGB emission could also help to solve the problem of supernovae type II explosion, thus providing an unified theoretical base for the GRB and SN phenomena.

The needed parameter range for such a PGB indicate an axion-like particle having a mass m_a of a few MeV, coupling to nucleons $g_{aN} \sim$ few $\times\ 10^{-6}$ and to electrons $g_{ae} \sim$ few $\times\ 10^{-9}$. This range of coupling constants coincides to that of the invisible axion with the Peccei-Quinn symmetry breaking scale $f \sim$ few $\times\ 10^5$ GeV. However, for such scale f a "true" axion would have a mass of few eV whereas we our PGB has a mass of few MeV,

[6] The possibility that the two photon decay of the axion-like particles with mass $0.15-1$ MeV could provide a mechanism whereby gravitationally collapsing massive stars may eject their outer mantles and envelopes in supernova explosions was first considered in ref. [31]. It should be noted, however, that the range for the coupling $g_{a\gamma}$ explored in ref. [31] actually corresponds to the vertical band of our Fig. 3 and it is strongly excluded by the experimental limits [29]. We thank S. Blinnikov for driving our attention to the ref. [31].

i.e. about a million times larger. Present experimental data and astrophysical limits cannot exclude this particle, however the relevant parameters' window is not far from the present experimental limits and it can be experimentally tested in the close future.

Acknowledgements

We would like to thank Sergei Blinnikov and Filippo Frontera for reading the manuscript and illuminating conversations. Useful discussions with Venya Berezinsky, Enrico Montanari, Amedeo Tornambé and Mario Vietri are also gratefully acknowledged.

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